Control of Vortex Breakdown in Critical Swirl Regime using Azimuthal Forcing

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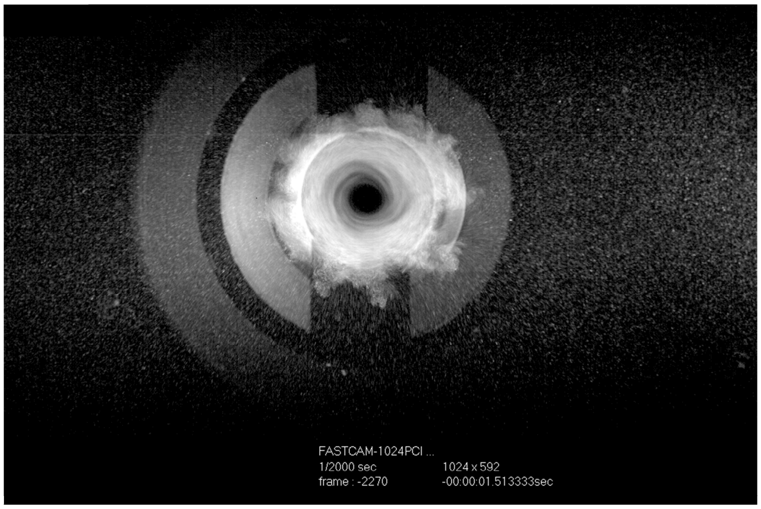
Stable Vortex 1500fps



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Let us first have a look at videos taken with a high speed camera.

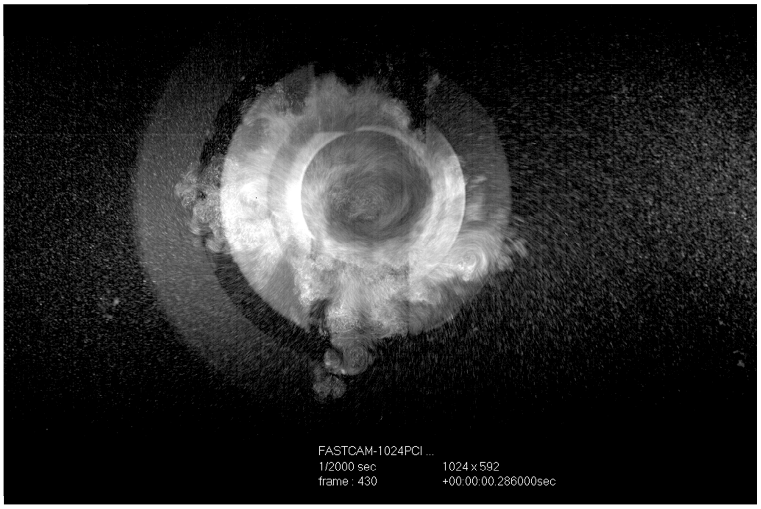
We see here the crossection of swirling jet. The jet is seeded with small particles and a laser is place in the crossplane of the jet.

The center of the vortex is marked by the dark area in the middle. Due to strong centrifugal forces the seeding is transported away from the center of rotation.

The entrainment is also visualized. The maximum flow velocity is about 30m/s.

If we increase the amount of swirl until vortex breakdown occurs, we get the following image.

Stable VB 1500fps

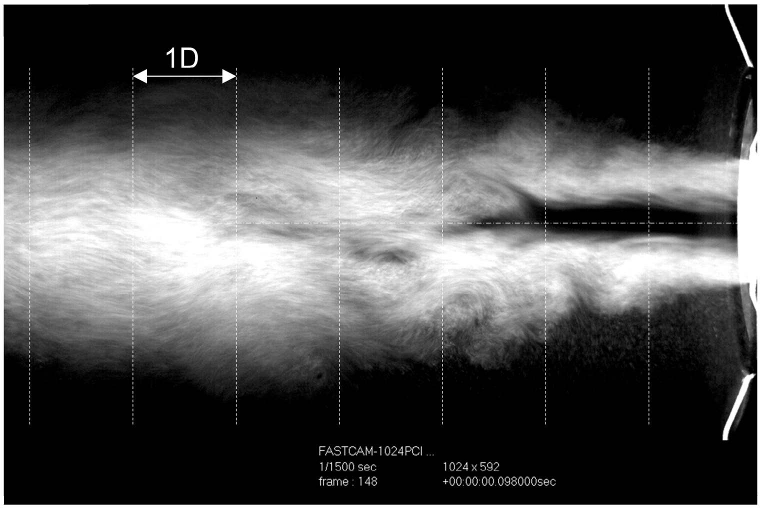


The black center disappeared and reversed flow entrains fluid filled with particles.

When looking carefully one can see by eye that there is a vortical structure rotating with the base flow.

We will later see that this can be considered as the precessing vortex core PVC.

Stable Vortex 1500fps



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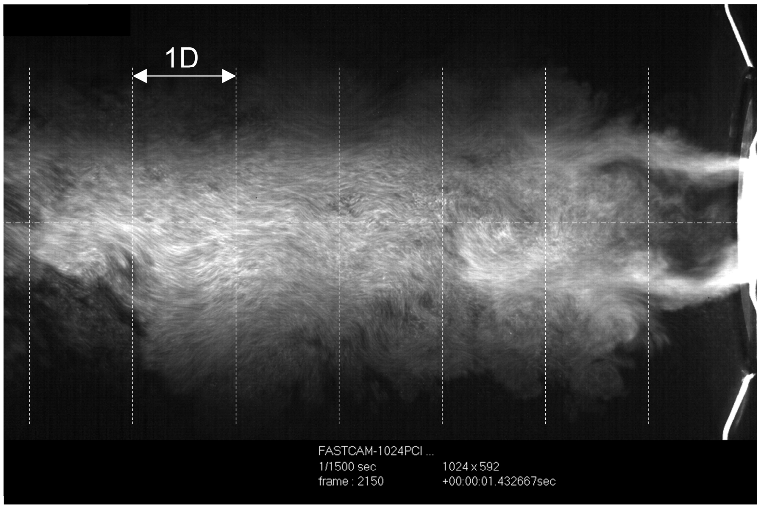
Lets go back to the lower swirl case again and look at the streamwise development of the flow.

The vortex core is visible up to x/D=2 to 3 . Further downstream turbulent mixing and the decay of azimuthal velocity cause the jet center to be seeded with particles.

Stable VB 1500fps



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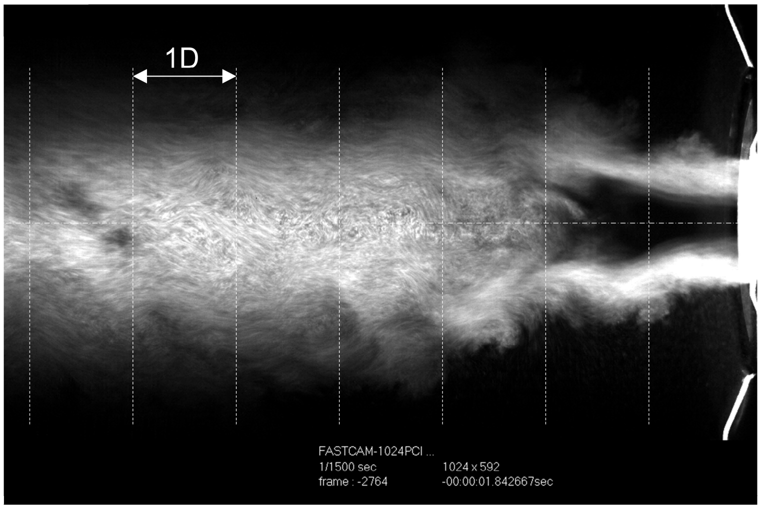
If we increase the swirl, VB moves upstream and the recirculation area stabilizes close to the nozzle exit.

We can see large scale oscillation dominating the entire flow field.

V-VB 25fps



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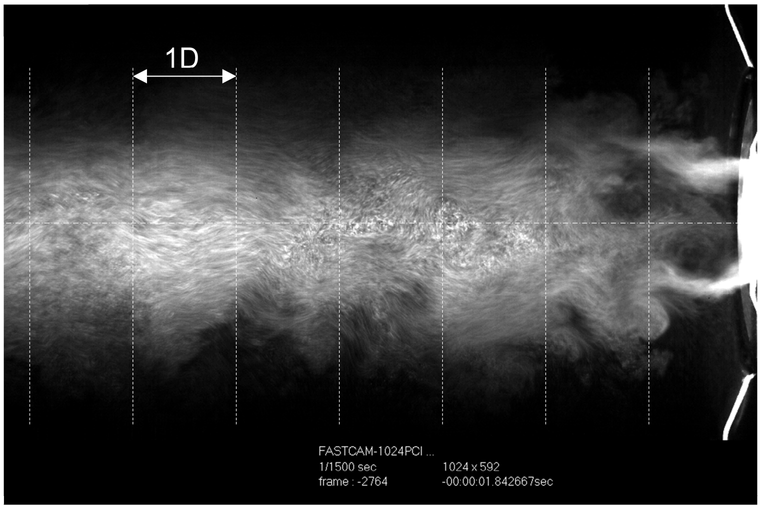
If we look at an intermediate swirl number we see that VB occurs further upstream and the region of reversed flow is strongly unsteady.

This is no approximately real time. In some cases we might even see the flow switching between the two extreme states as can be seen here

VB-V-VB 25fps



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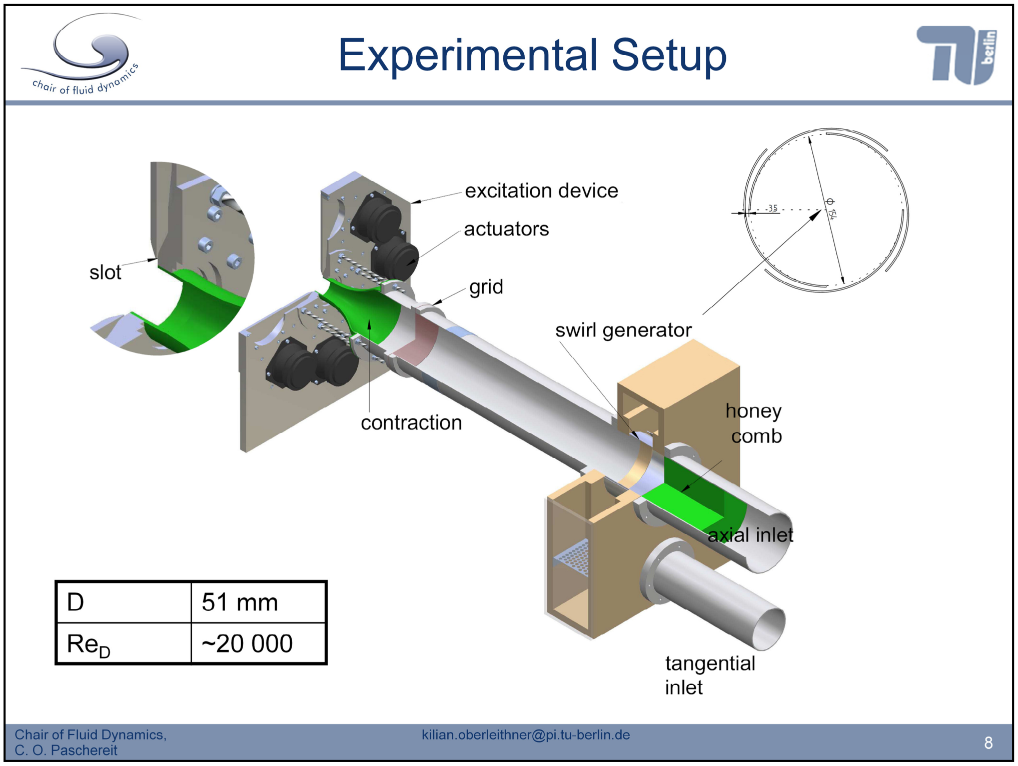


D	51 mm
Re_D	~20 000

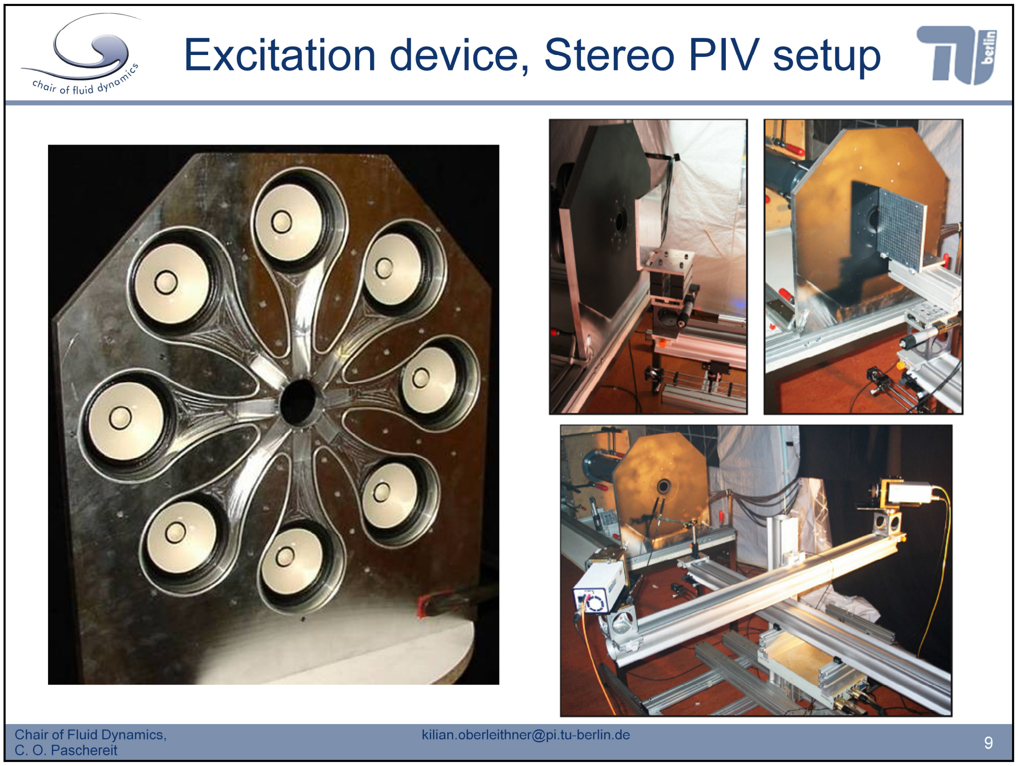
We therefore generate a swirling jet in air. It is done by combining two air streams. The first is guided through this long tube providing the axial momentum. The second is guided through four tangential slots which are inside this box providing the tangential momentum.

The advantage of this setup is that the swirl number can be changed while keeping the mass flow constant.

Downstream this tube the rotating fluid goes through a contraction and is released through a Nozzle with 5 cm diameter.

The near field of the swirling jet was measured by using   Stereo PIV.

At the nozzle lip acoustic excitation was applied. Therefore this metal plate was designed.



The excitation device with the nozzle exit in the center. The front plate has been removed for the picture to see the speakers and the wave guide.

The PIV setup using two cameras and a hotwire in parallel. The HW will be used to phase-lock the measurement.

Data was taken in streamwise and crosswise direction.

Natural Flow

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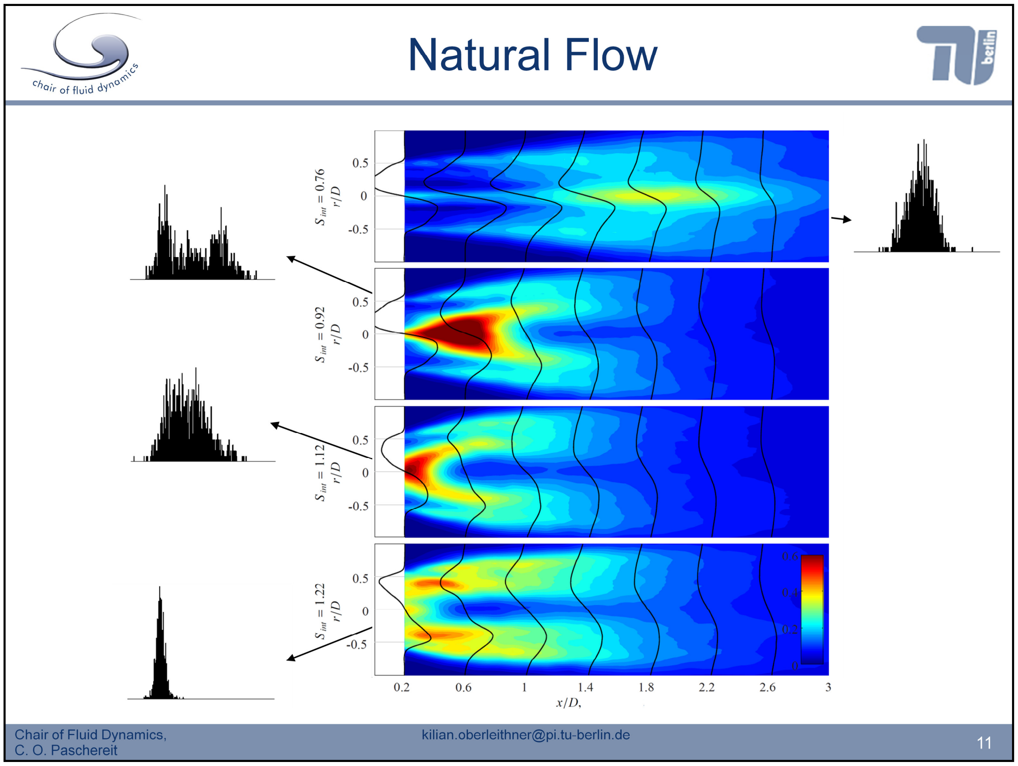
Lets look first at the unforced natural flow.



Thats how tha profiles of the mean axial velocity looks like . These for cases will deal as the baseline cases.

The gray gray area marks the region of reversed flow. It is usually the definition of vortex breakdown.

Accordingly at the lowest swirl number we have no VB to occure.

With higher swirl VB appears and moves upstream.

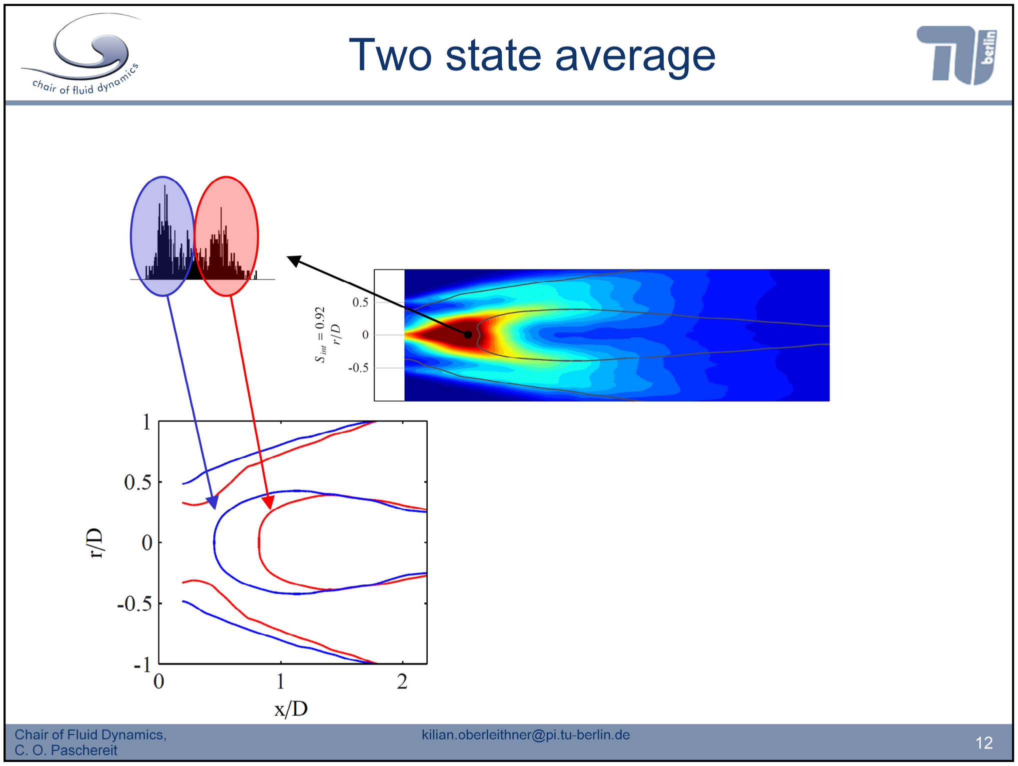
If we look at the half velcoity line which idealy marks the center of the shear layer, we see that VB causes a second shearlayer to appear.

Of course there is also an axial and azimuthal velocity component which is important but lets look at the TKE at this point.

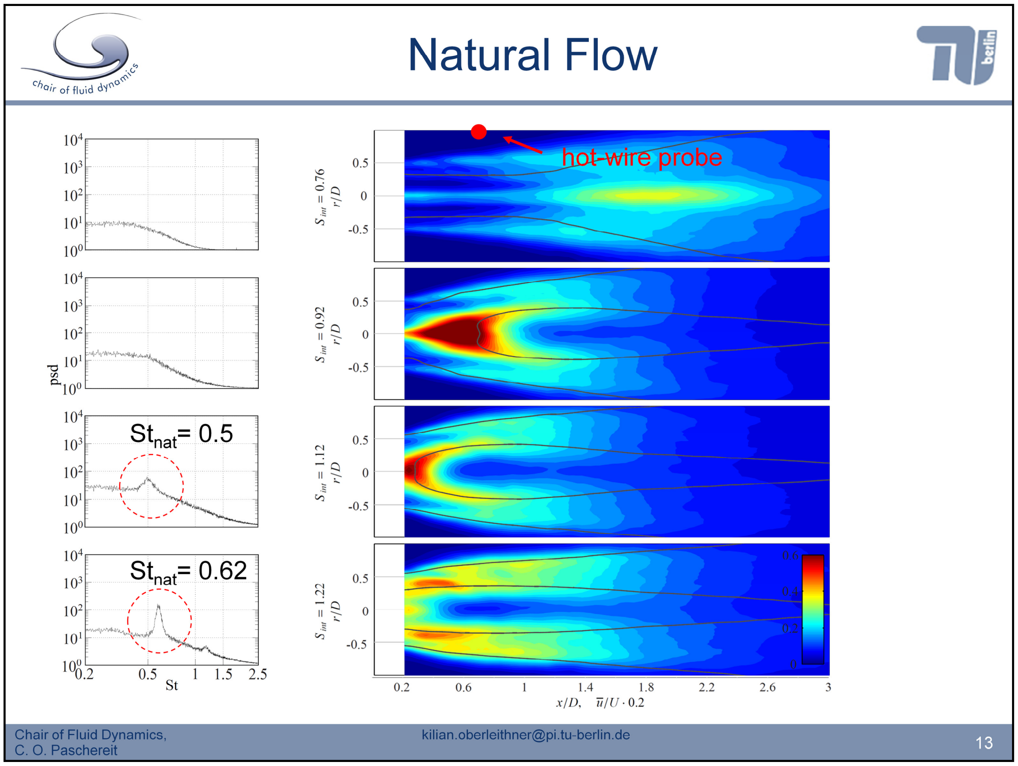
It matches quite well the location of the half velocity line. Most stryking is the high level near the jet axis upstream of VB.

If we plot a velocity histrogram we see that the first three cases show vary strong deviation.

In the second case we may even see two peaks in the histogram.



If we take this extrem case as an example, and average the PIV snapshots of both states seperately, we see that the two peaks are caused by an axial desplacement of the region of VB, as shown here using the half velocity lines .

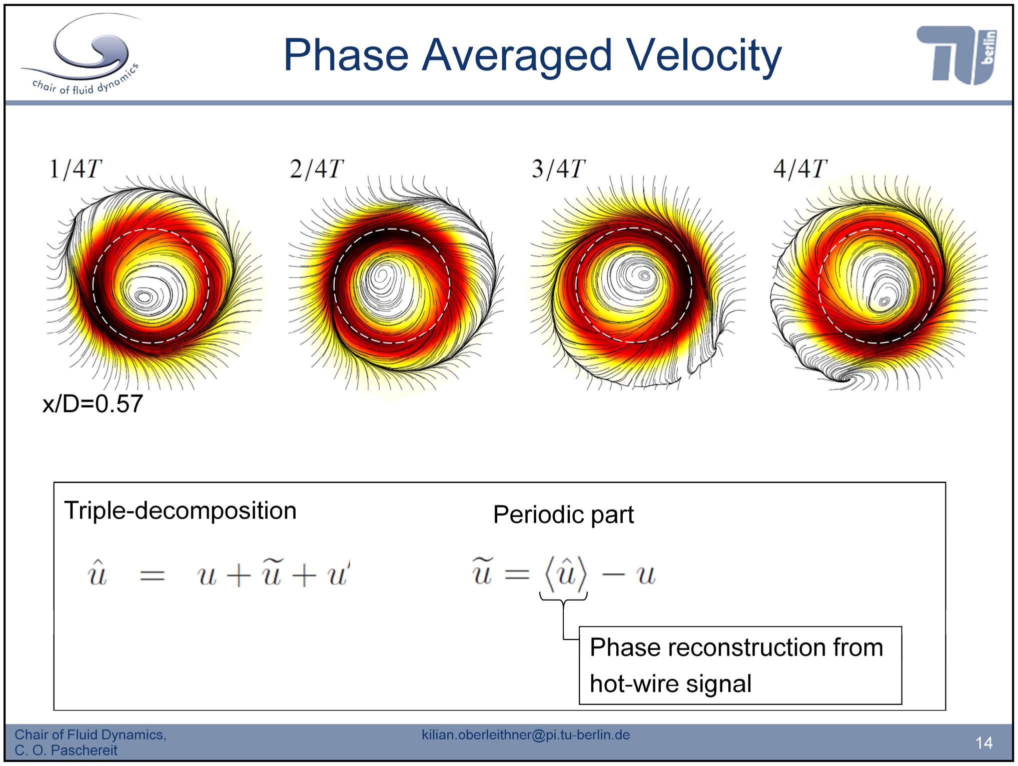


Lets get back to our four caes and look at hw spectra.

What we founbd was that a destinct peal appears for the higher swirl cases.

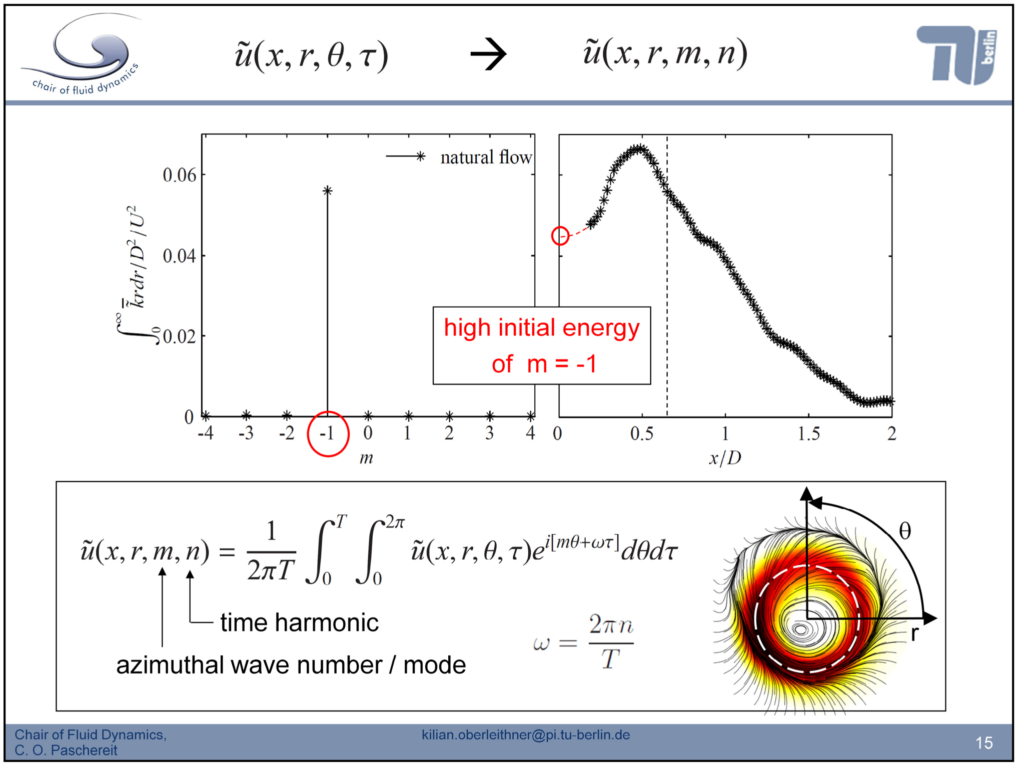
This could be found in the entire flow field geving us the frequency of the large scale fluctuation seen in the flow viz.

It seems to areise from the background noise when VB occures and overwhelms the entire nearfield of the jet.



We may than phase average the PIV data and see that this peak corresponds to a single vortex rotating with the base flow, which might be associated with a PVC.

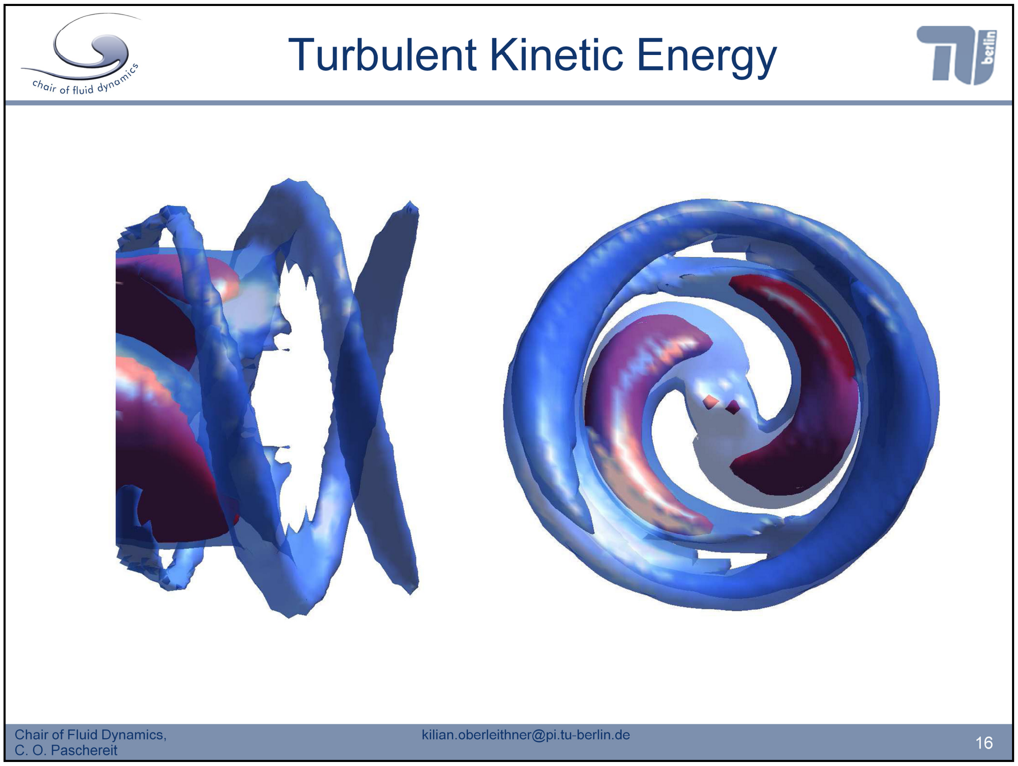
It is located in the inner axial shear layer and its azimuthal phase velocity is equal to the base flow rotation.



When we transform the velocities into the Fourier space, we see that most of the phase locked energy is captured by the mode m=-1.

Defining negative modes as rotating in direction with the base flow.

We further see that the energy of this mode is starting at a considerably high level at the nozzle exit and just grows a little more before decaying . This is an indication ´that this mode is self excited.

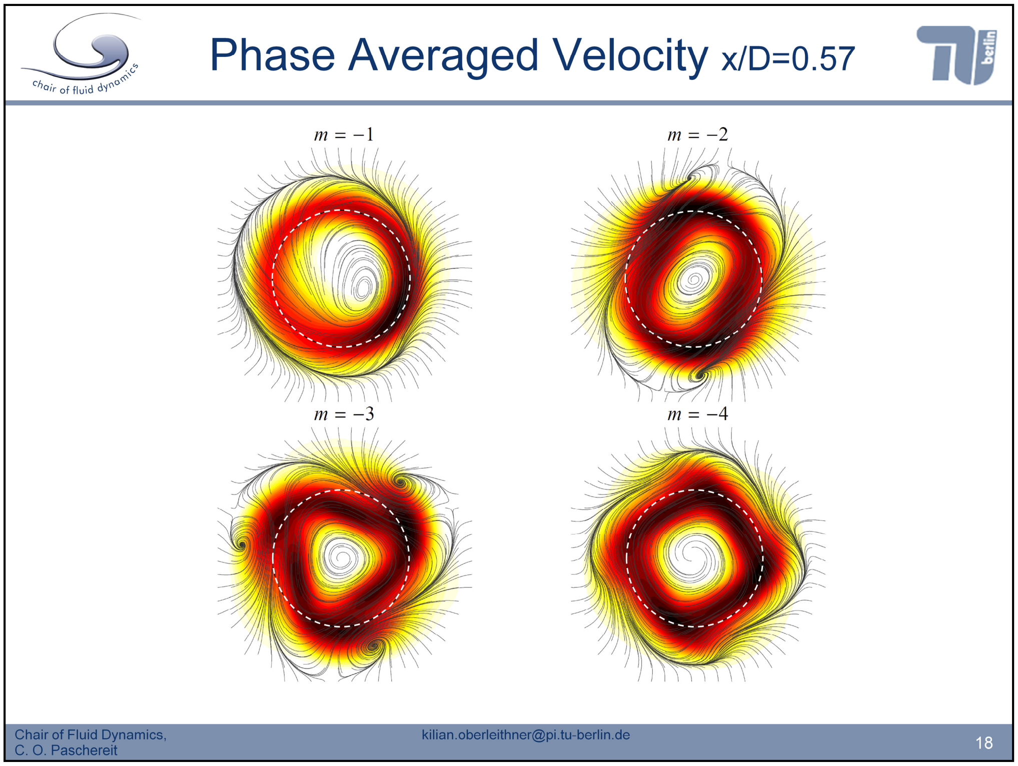


This slide shows the reconstruction of the of the 3d flow field showing the turbulent kinetic energy of the phase locked mode.

The red contour is twice as high as the blue one showing the strong concentration of energy initially distributed in the inner shear layer.

It decays quickly while the energy of the m = -1 mode is growing . There seems to be a strong coupling of these two shear layers. While the pacemaker is located in the jet center.

Forced Flow



This are plots of the phase locked flow at a individual phase angle when forcing mode -1 to m-4.

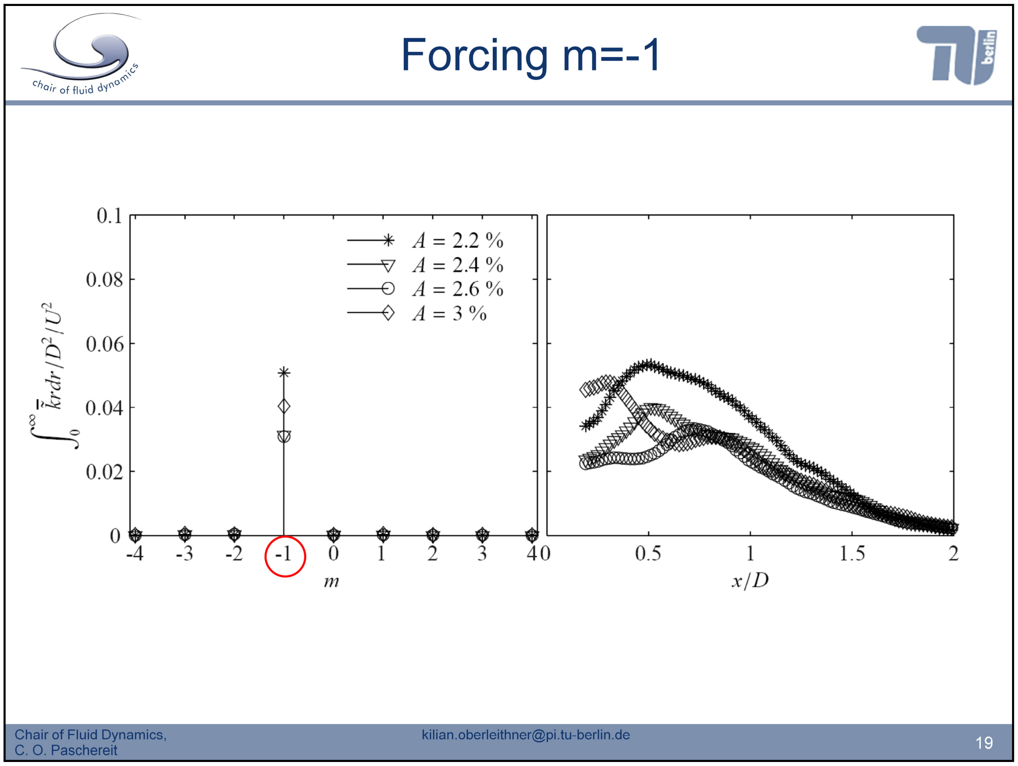
The color show the axial velocity with the recirculation zone in the middle.

Data was taken at roughly the axial distance of maximum amplification.

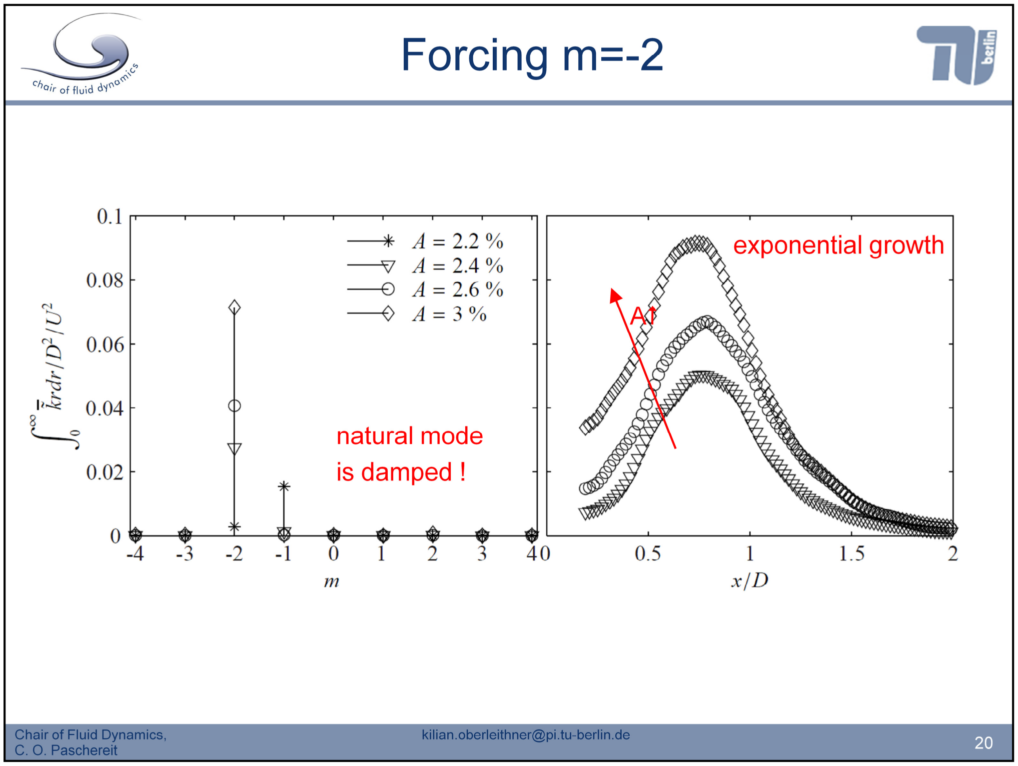
Modes rotating in the opposite direction of the base flow were not amplified.

We that when forcing m = -2 to m = -4 the vortices are basically located in the outer shear layer, while forcing m = -1 is in the inner.

Lets look closer at the first two cases and lets see if we can find some hints to the nature of the instability.



Forcing m = -1 at various amplitudes does not show a clear response. The energy contained in this mode is rather decreasing with increasing amplitude but not in a linear way. Certainly there is some complicated interaction between the outer and the inner shear layer.



If we force the flow at m = -2.

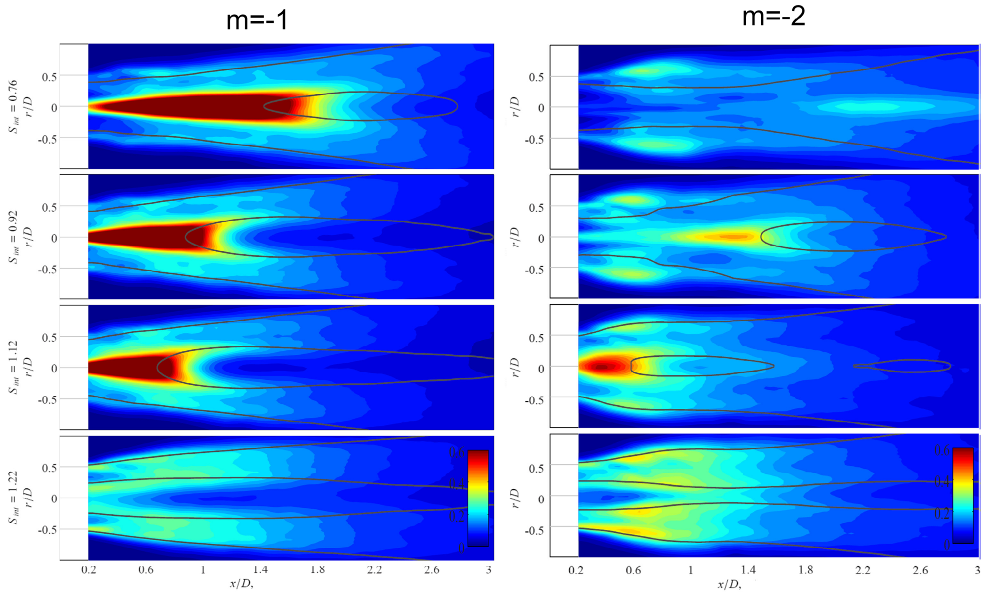
We can see the following,

The amplitude of the natural occurring mode is damped out when the forcing amplitude is high enough.

Than the energy of the excited mode is growing exponentially starting at a relatively low level reaching a high maximum before decaying.

Repose to an increase of amplitude is approximately linear.

TKE



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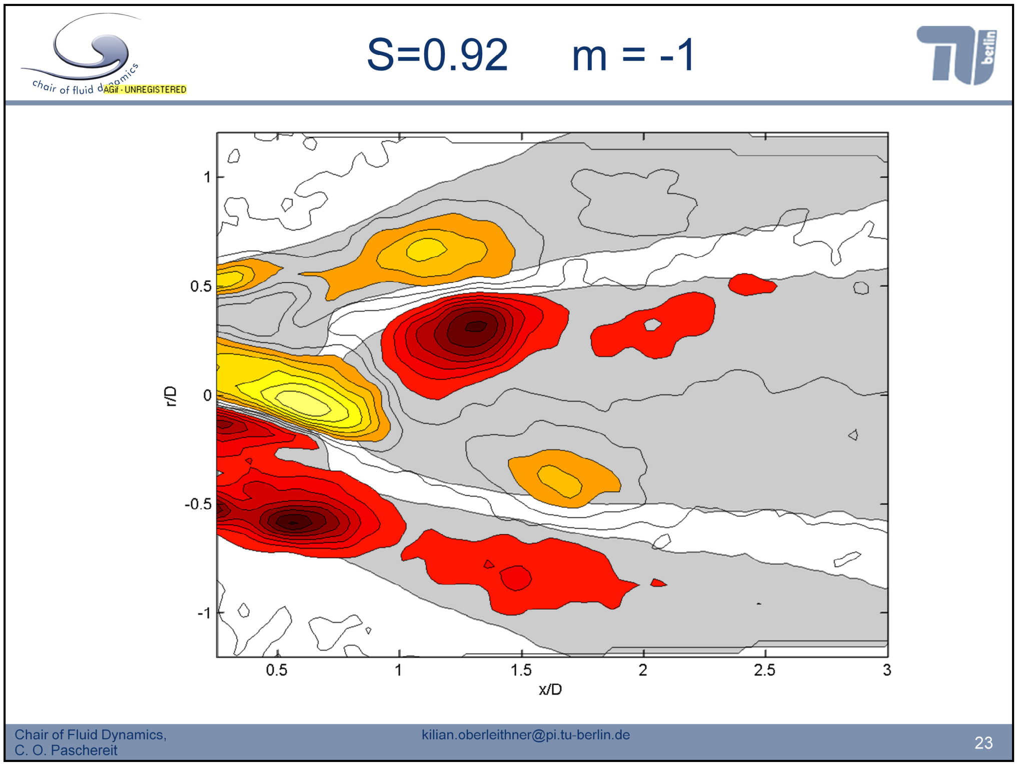
Clunclusion/Descussion

- ! At critical swirl number VB is highly unstable
- ! m=-1 dominates the entire near-field when VB occurs
- ! Instabilities growing in the outer shear layer are CU
- ! Forcing m=.-1 causes PVC to lock in and VB is stimulated
- ! Forcing m=-2 causes PVC to be damped and VB is delayed

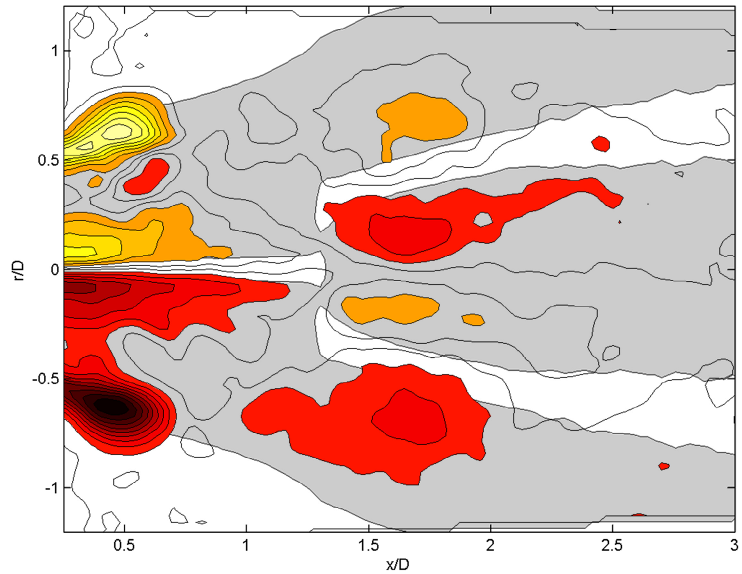
- ? Is concept of AI/CI applicable for PVC and VB
- ? Is m=-1 self excited globally unstable mode?
- ? What is the reason for the jet-closure downstream VB
- ? What selects the most amplified frequency

- ⇨ Transient experiments
- ⇨ Linear stability analysis
- ⇨ Dynamic model

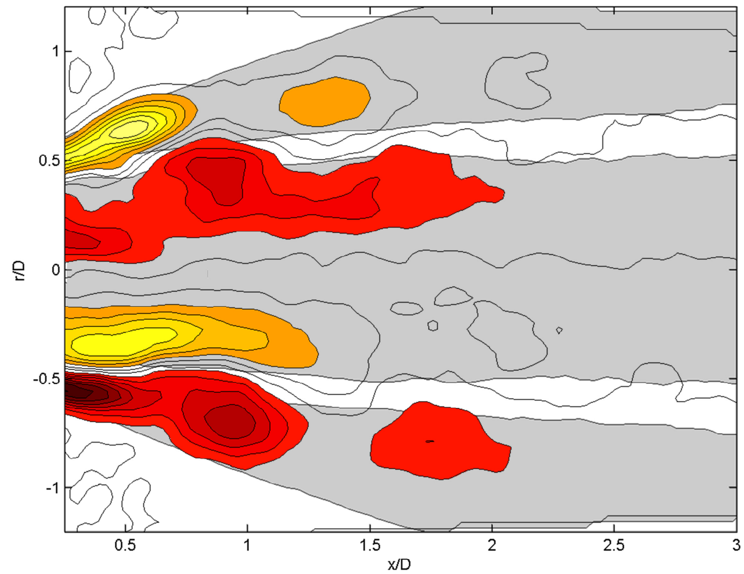


Before I conclude the results I d like to show a few videos of the phase-locked vorticity. For two cases.

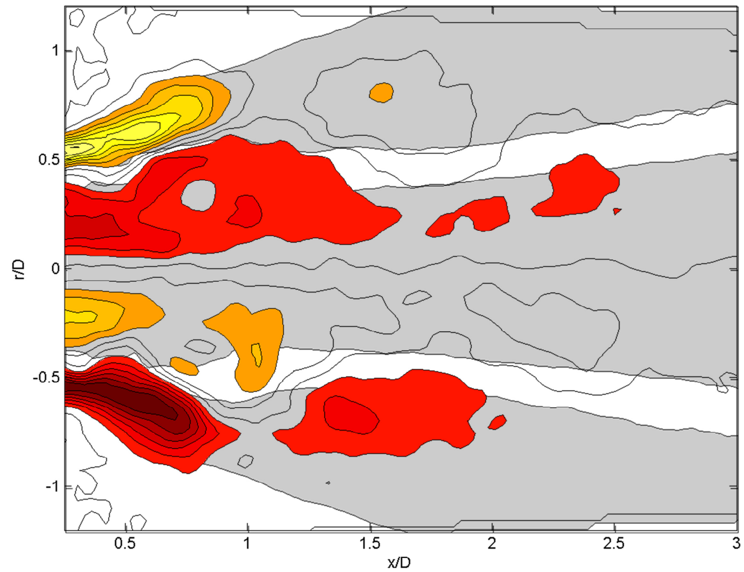
S=0.92 m = -2

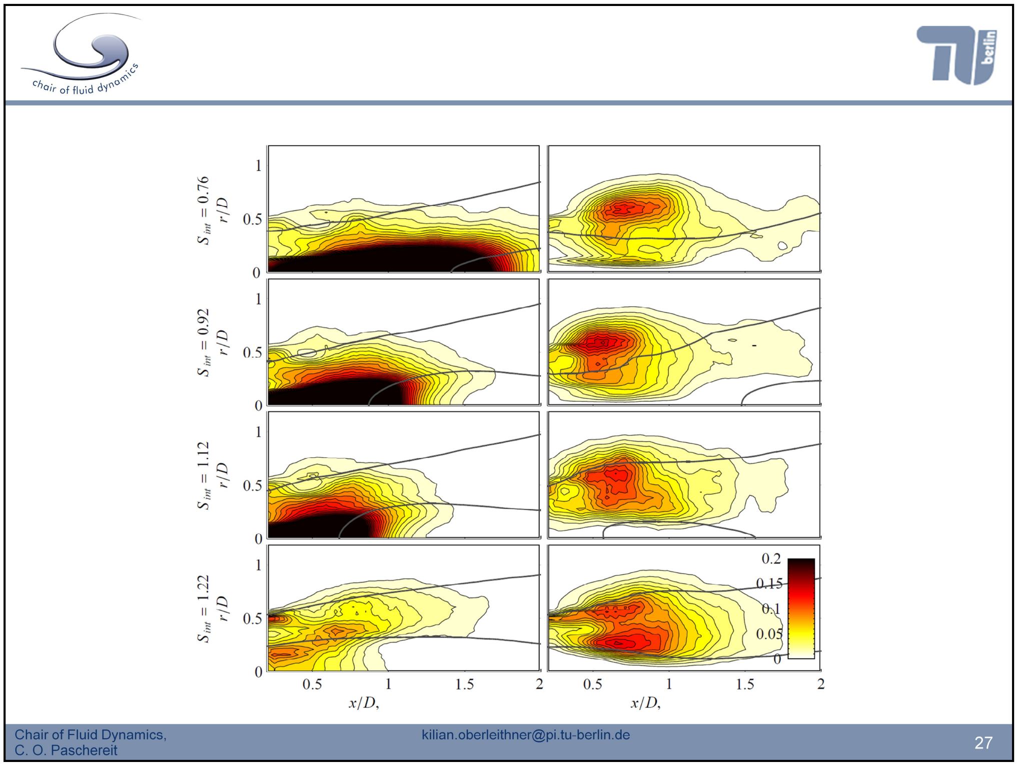


S=1.22 m = -1



S=1.22 m = -1





So I would finally go back to the four swirl cases and see how the flow responses to either forcing m = -1 ro m = -2.

On the left we see the flow forced at m = -1

We see that the PVC locks onto the applied forcing also for lower swirl number causing this high TKE at the jet center.

The amplification of this instability causes VB to occur at a lower swirl number.

The opposite can be seen when forcing the flow at m=-2 which is basically growing in the outer shera layer causing VB to move downstream .

There is no energy at the center of the vortex showing that the precessing has been damped.

The mean flow is most altered at the swirl numbers were VB is unstable.